Spatial distribution of carbon over an eroded landscape in southwest Wisconsin[☆]

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Abstract

Spatial distribution of carbon (C) within a soil profile and across a landscape is influenced by many factors including vegetation, soil erosion, water infiltration, and drainage. For this reason, we attempted to determine the soil C distribution of an eroded soil. A three-dimensional (3D) map of a 0.72 ha field with a Dubuque silt loam soil which has three levels of erosion (slight, moderate, and severe) was developed using soil distribution and profile data collected using a profile cone penetrometer (PCP). This map displays the distribution of the total depth of the Ap and Bt1 horizons and the upper part of the 2Bt2 horizon. A map of soil C distribution was created for this landscape using C content information obtained from soil samples. Based on the C distribution in the upper two horizons, a 3D viewing was developed of soil C distribution for this eroded landscape. The 3D assessment of C distribution provides a better means of assessing the impact of soil erosion on C fate. It was estimated that there were 52 Mg ha^{-1} of total C in the surface (Ap) horizon and 61 Mg ha^{-1} in the Bt1 horizon for the 0.72 ha area. This increase in C with depth in the soil can be attributed to an increase in clay content and C leaching resulting in stable carbon–clay complexes. The C content was 16.0, 17.5, and 19.0 g kg^{-1} for the Ap horizon in the slight, moderate, and severe erosion levels, respectively. However, it was estimated that the total C amount in the respective Ap horizons was 28, 14, and 10 Mg ha^{-1} for the slight, moderate, and severe areas. The Bt1 horizon had 31, 19, and 11 Mg ha^{-1} of C in the slight, moderate, and severe areas, respectively. For the 0.72 ha area, 25% was severely eroded with 31 and 44% being moderate and slight, respectively. Soil C distribution information, such as that presented here, can be very valuable for soil management and could be used to determine possible C storage credits.
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1. Introduction

Erosion can change the biological, chemical, and physical properties of a soil. Frequently these changes in soil properties can be attributed to changes in C content of the eroded soil. It is difficult to determine a priori the impact of erosion on a given soil. For

example, Lowery et al. (1995) found that in most cases erosion resulted in a decrease in soil C, but in a Dubuque silt loam soil, the C content in the surface increased with soil erosion. It has been reported that organic C compounds interact more readily with clay than silt or sand particles (Mortland, 1970; Greenland, 1971; Bohn et al., 1985; Stevenson, 1994; Sparks, 1995).

Variability in C with erosion is related to soil profile characteristics. Three classes, or levels, of erosion have been established by the Soil Survey Staff of the formerly known Soil Conservation Service (currently Natural Resources Conservation Service) of the United States Department of Agriculture (Soil Survey Division Staff, 1993). Class 1, or slight erosion severity, is defined as a loss of less than 25% of the original A horizon or of the uppermost 20 cm if the original A horizon was less than 20 cm thick. Moderate erosion severity, Class 2, is described as a loss of 25–75% of the original A horizon or of the uppermost 20 cm if the original A horizon was less than 20 cm thick. A loss greater than 75% of the original A horizon or of the uppermost 20 cm if the original A horizon was less than 20 cm thick is considered as severe erosion, or Class 3. The reasoning behind these guidelines is that as soil erosion progresses, surface soil layers are removed exposing underlaying layers. It should be noted that we are referring to past erosion and not present or ongoing erosional process. In the Dubuque silt loam case described by Lowery et al. (1995), the topsoil was removed by erosion in a soil where C was leached to the subsoil and formed clay complexes.

Increases in clay content have been reported in the Ap horizon of some eroded soils. Olson and Nizeyimana (1988) observed an increase in clay content in eight eroded soils throughout Illinois, while Chengere and Lal (1995) also reported an increase in clay content after removal of the surface 20 cm of a silty clay loam soil to simulate severe erosion. This increase in clay content in the Ap horizon is attributed to the exposure and subsequent mixing by tillage operations of lower soil horizons (B) rich in clay. It appears that under certain conditions, as the clay content of the surface horizon increases as a result of erosion, the carbon content of the surface soil is also increased.

The erosional process can change important soil properties, such as organic matter content and particle size distribution, which in turn can affect soil bulk density, hydraulic conductivity, water retention, and other important soil properties including overall crop productivity. Therefore, the objective of this study was to determine soil C distribution of an eroded soil, including the development of a 3D map of soil to allow the calculation of total C distribution.

2. Materials and methods

The study was conducted in the driftless-region of southwestern Wisconsin, at the University of Wisconsin–Madison Lancaster Agricultural Research Station ($42°52'$N, $90°42'$W). Soil at the research site is a Dubuque silt loam (fine-silty, mixed, mesic, Typic Hapludalfs). This soil was formed in loess underlain by a red clay residuum with a sub-angular blocky structure (Glocker, 1966). Depth to the red clay residuum ranges from 0.45 to 0.95 m. The site was 120 m × 60 m and it was located on a southwest facing slope (10–14%). In 1985, three levels of past erosion (slight, moderate, and severe) were identified using the depth to the red clay residuum (2Bt2 horizon) as a baseline (Fig. 1) (Andraski and Lowery, 1992). Three 7.3 m × 13.7 m plots were established for each of the three erosion levels in 1985 in the 0.72 ha field. This area has been cropped in continuous corn (*Zea mays* L.) for the last 16 years.

Soil profile penetration data were collected with a PCP in a 10 m × 10 m grid. The PCP consisted of a $30°$ cone with a 2.0 cm base diameter, threaded to a 1.25 cm diameter × 1.5 m long stainless steel rod (ASAE, 1999). Penetration force was measured with a 1360 kg load cell, while depth was measured using a string potentiometer (Rooney and Lowery, 2000). The PCP was pushed into the soil profile at a rate of 5 cm s^{-1} with a hydraulic soil probe mounted on a truck. An electronic data logger was used to collect load cell and string potentiometer data every 0.05 s. A digital elevation model (DEM) was created from data collected with a differentially corrected Global Positioning System (GPS) attached to an all-terrain vehicle. Profile cone penetrometer sampling points were also geo-referenced with a GPS.
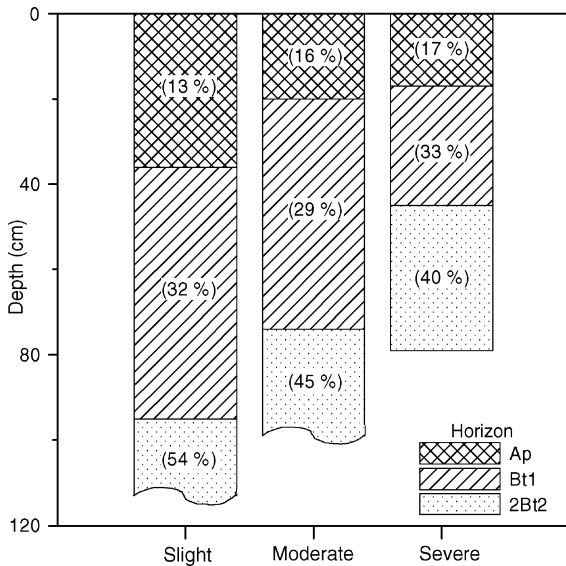
Fig. 1. Thickness of the Ap, Bt1, and 2Bt2 soil horizons for the slight, moderate, and severe erosion levels. Numbers in parenthesis represent the clay content for each horizon (adapted from Andraski and Lowery, 1992).

Penetration force data were transformed into cone index (CI) using the formula:

$$CI = \frac{F_p}{A_c}$$

where F_p is the penetration force, and A_c the basal area of the cone. At each recorded depth, there was an associated CI value, thus creating a continuous curve for the entire profile at each sampling point. These data were then analyzed using the cluster observation procedure in Minitab (2000), with the standardized variables option selected, and using the Squared Pearson and Ward method for distance measure and linkage method, respectively. The cluster procedure identifies clusters, or groups, of observations that are similar. Profile CI values were clustered into three clusters which corresponded to slight, moderate, and severe erosion.

Soil particle size distribution (PSD) was determined for each horizon by the pipette method (Gee and Bauder, 1986). Total carbon was determined on soil samples collected using a 1.9 cm diameter hand push probe in 10 cm increments to a depth of 50 cm. Five samples were taken from each subplot at each

depth increment and combined to form one composite sample per depth for each erosion plot. Soil samples were dried in an oven at 105 °C for 24 h. After drying, soil samples were ground by hand to pass a sieve with 149 μm openings (100 mesh). Total C was determined by dry combustion with a Tekmar-Dohrman DC-190 carbon analyzer (Rosemount Analytical Inc., Dohrman Division, Santa Clara, CA) equipped with a solid sampler unit.

The generalized linear model (GLM) procedure in Statistical Analysis Systems (SAS) software was used to conduct analysis of variance of soil C and PSD data (SAS Institute, 1989). Mean separation was performed using least significant difference (LSD) multiple-range test procedure. Calculations for total C amounts for the different horizons were adjusted for soil bulk density (data not shown), area, and soil volume, determined from horizon thickness data.

3. Results and discussion

The Dubuque soil at the research site has a clay-rich, soil residuum (2Bt2 horizon), thus as erosion occurred at this site, the 2Bt2 horizon became closer to the surface (Fig. 1). Because of this erosion process, depth to 2Bt2 horizon has been used to determine the severity of past erosion at this site as well as in other locations (Bruce et al., 1988; Olson and Nizeyimana, 1988; Andraski and Lowery, 1992; Cihacek and Swan, 1994; Lowery et al., 1995). Greater clay contents are generally observed at shallower depths with increasing soil erosion. Particle size distribution data for this site follow this trend, showing increasing clay contents at shallower depths as soil erosion level increases (Fig. 1). As it will be presented later in this paper, this increase in clay had an impact on the C content in the surface soil.

In the top 20 cm of the soil profile the order of C content in soil for the different erosion levels was, severe > moderate > slight, but these differences were not statistically significant (Table 1). It is believed that there is a greater interactions between organic materials and clay particles than sand and silt particles. This interaction results in greater organic C contents in the soil profile where there is a greater clay content, especially when C moves through the soil, as soluble C, much the same as soil clay migrates to

Table 1
Soil C content for each erosion level (slight, moderate, and severe) at different depths

Depth (cm)	Erosion level (g kg^{-1})		
	Slight	Moderate	Severe
0–10	18.3 (3.5)	19.0 (3.0)	21.7 (2.1)
10–20	13.7 (1.2)	16.0 (1.7)	16.3 (3.5)
20–30	11.5 (1.0)	9.0 (1.7)	10.0 (3.0)
30–40	10.3 (3.1)	7.0 (1.0)	8.5 (0.6)
40–50	9.3 (2.5)	7.7 (1.5)	8.0 (1.2)

Numbers in parenthesis represent standard deviations; differences between erosion levels at the same depth are not statistically significant ($P < 0.10$).

lower parts of the soil profile (Mortland, 1970; Greenland, 1971; Bohn et al., 1985; Stevenson, 1994; Sparks, 1995). Eroded Dubuque soil, which has its clay-rich subsoil closer to the soil surface, has an increase in soil C in the upper soil profile in comparison to a non-eroded Dubuque soil. Over time the addition of organic matter from plant residues promotes greater accumulation of soil C in the surface horizon of eroded soil where the clay content is greater than slightly eroded soil. This can result in the soil C content differences observed between the erosion levels. Deeper in the profile of each erosion level, the order of C content in soil changed to slight > severe > moderate. Lowery et al. (1995) also reported increasing organic C content, determined by the Walkley–Black method, with increasing erosion

severity for this same research site. However, at 11 other locations in the Midwest, they found the reverse trend of decreasing C with increasing erosion (Lowery et al., 1995). For this reason, we believe that differences in soil C content measurements between treatments reported here are representative of changes in organic C content, and not inorganic soil C. Over extended periods of time, C was leached to the 2Bt2 horizon in this soil. This is in agreement with the findings of Arriaga and Lowery (2003) at this site, where greater increases in C content were found deeper in the profile of severely eroded soil that had a greater clay content than other erosion levels.

A spatial and 3D map/representation of the 0.72 ha area was developed using data obtained with a PCP as described by Rooney and Lowery (2000) and a clustering technique described by Grunwald et al. (2001). The cluster groups were used to create the 3D representation with Environmental Visualization System software (C-Tech Development Corporation, Huntington Beach, CA) (Fig. 2). The unique properties of this soil profile, with the well-defined depth to the 2Bt2 horizon, allowed for development of a two-dimensional (2D) map showing the spatial distribution of the different erosion levels of this soil (Fig. 3). This map was created using data from the PCP and GPS to locate soil depth distribution across the 0.72 ha area. By combining soil C data from the nine plots (Table 1) with the soil erosion level distribution map (Fig. 3), it
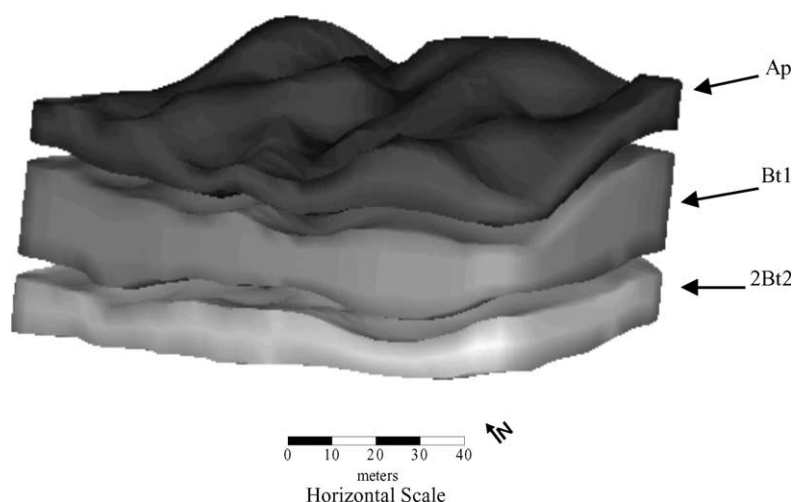

Fig. 2. Representation of the Ap, Bt1, and 2Bt2 soil horizons in three dimensions at the Lancaster site. Vertical axis was exaggerated ten times, and the thickness of the 2Bt2 horizon was greater than presented here.
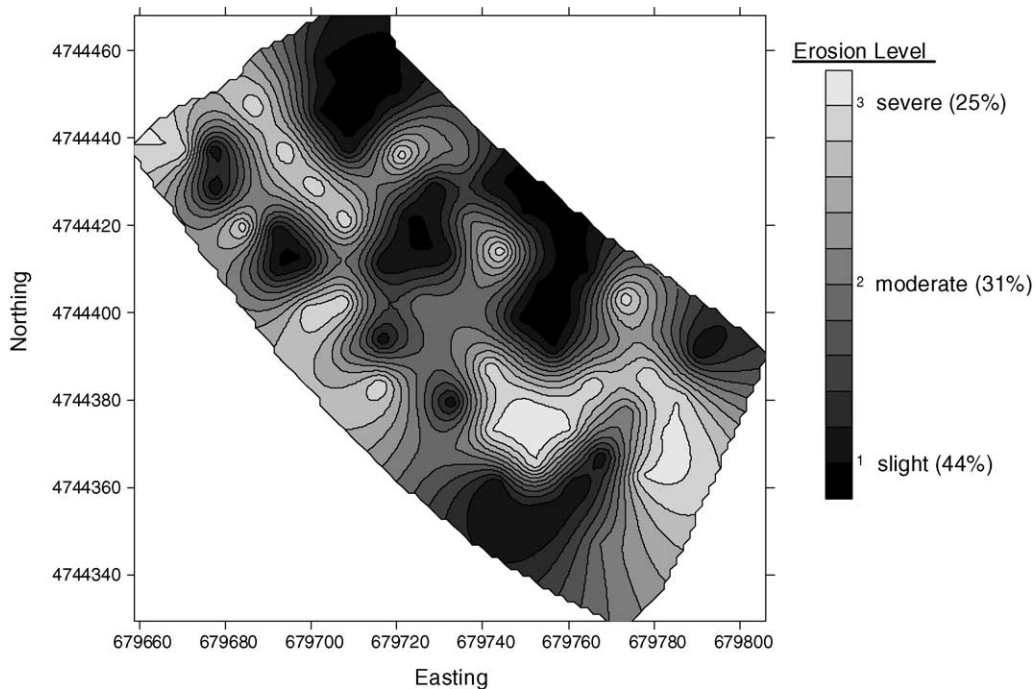
Fig. 3. Spatial distribution of erosion. Numbers in parenthesis represent the percentages of the total area that each erosion level covers.

was possible to construct 2D maps of soil C distribution for the Ap and Bt1 horizons (Fig. 4). Figs. 5 and 6 demonstrate how C distribution data can be visually compared to 3D soil maps. Areas with greater percentage of C in the surface horizon correspond to areas of greater soil erosion, displayed as thin areas in the Ap horizon (Fig. 5). Locations where the thickness of the Ap horizon were greater correspond to less erosion. When information from the 3D representation was combined with the C distribution map, an estimate of the total amount of C for the various erosion levels was obtained (Table 2). No existing literature has been found that attempts to quantify soil C as a function of past erosion on a landscape scale as was done in this research.

While slightly eroded areas have less soil C in the Ap horizon (Table 1), the assessment of the 3D soil representations showed the greatest percentage of this land was in the slight erosion category (44% slight, 31% moderate, and 25% severe, Fig. 3). Thus, there was a greater volume of C stored in the slight erosion areas for both horizons (Table 2). While it was clear that there was a noticeable increase in C with increasing erosion at this site, the trend of total

amount of C for each erosion level was reversed. Total C amounts were 28, 14, and 10 Mg ha^{-1}, respectively, for the slight, moderate, and severe erosion Ap horizons. The reason for this reverse in trend for the total C amount with respect to erosion for this soil was that the total amount of soil were 20, 10, and 7 Mg ha^{-1} for slight, moderate, and severe erosion areas, respectively. A similar trend in soil C was noted for the Bt1 horizon with decreasing total amounts of C with increasing erosion. Thus, it is important to consider the entire volume of soil when assessing C distribution for eroded landscapes. However, when the Ap horizon was compared to the Bt1 horizon there were 9 Mg ha^{-1} more C in the Bt1 horizon than the Ap horizon (Table 2). This can be attributed to C leaching to this horizon that formed carbon–clay complexes and a larger amount of soil in the Bt1 horizon.

Using data from another study that focused on the effect of long-term manure additions on soil properties at this same site (Arriaga and Lowery, 2003), we estimated that the soil at this location has the potential to store about 3.9, 4.3, and 4.5 g C kg^{-1} soil of additional C for the slight, moderate, and severe erosion levels, respectively.
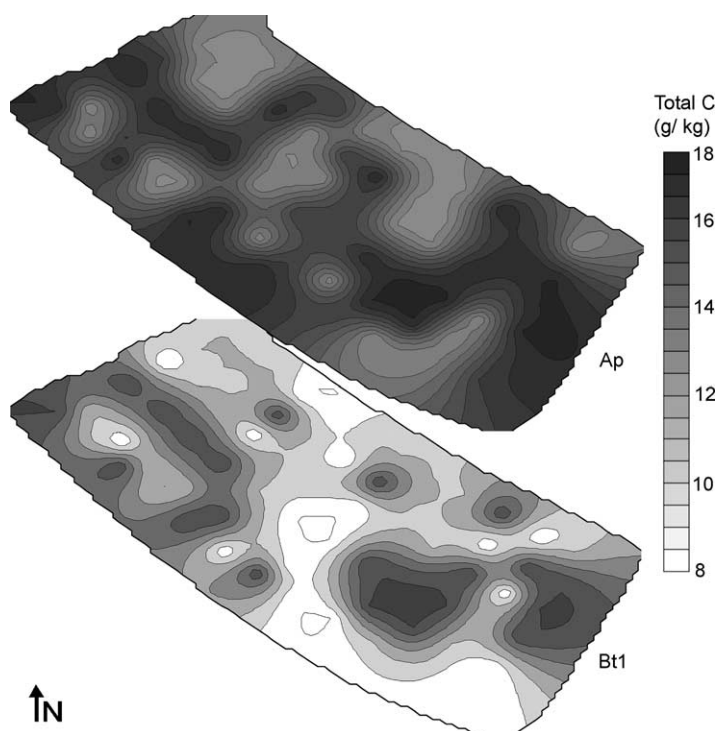
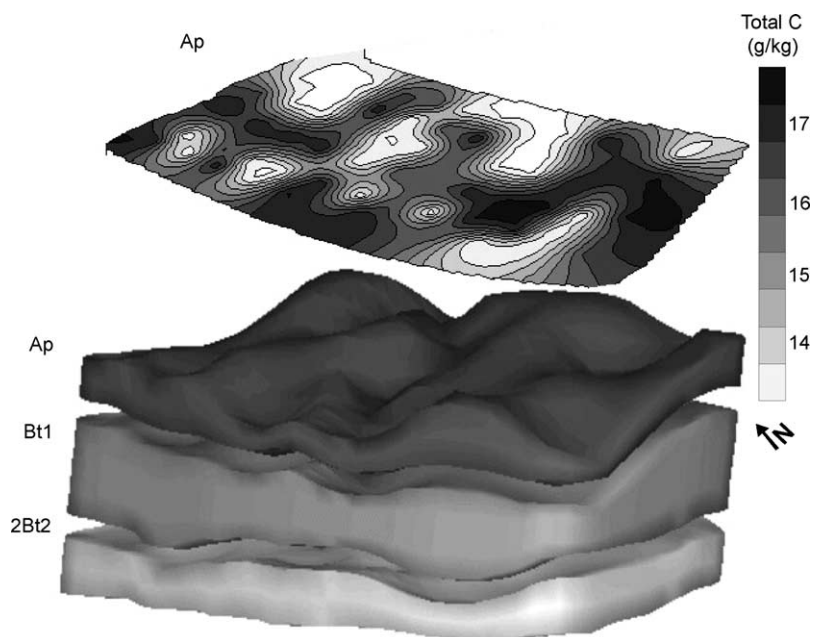Fig. 4. Spatial distribution of soil C in the Ap and Bt1 soil horizons.

Fig. 5. Effect of elevation and soil horizon thickness on soil C distribution of the Ap soil horizon.
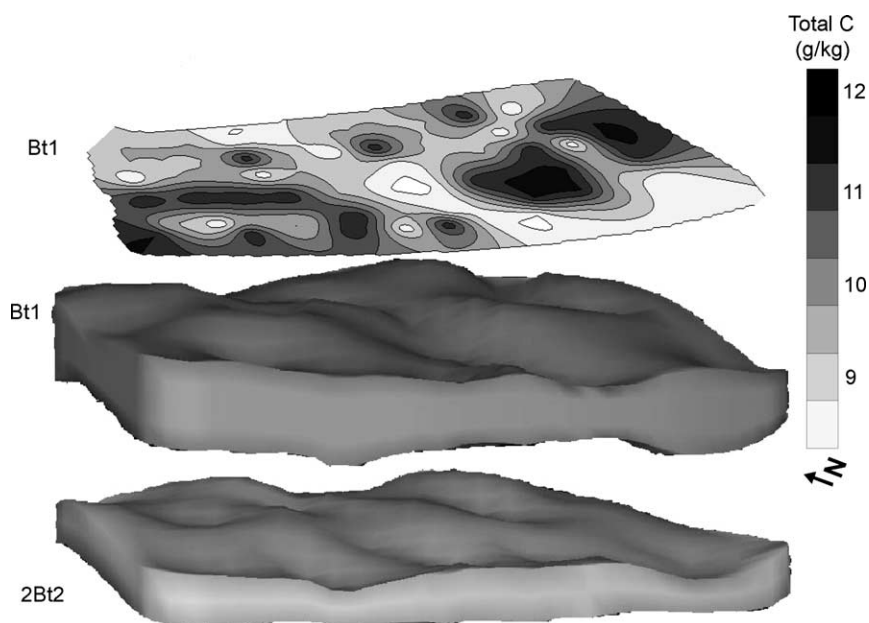
Fig. 6. Relationship between soil horizon thickness and soil C distribution in the Bt1 soil horizon.

Table 2
Calculated total soil C amounts for each erosion level (slight, moderate, and severe) in the Ap and Bt1 soil horizons

Erosion level	Total carbon in horizon (Mg ha^{-1})	
	Ap	Bt1
Slight	28	31
Moderate	14	19
Severe	10	11
Total	52	61

Calculated amounts are corrected for soil bulk density.

4. Conclusions

The increase in C content in the surface soil horizon with increasing erosion level had little influence on the total distribution of C over the landscape. There was also a noticeable increase in clay content with increasing erosion severity in the surface of eroded soil. It appears that this increase in clay was caused by the removal of surface soil layers and the subsequent exposure of clay-rich underlying layers. The clay formed organic C-clay complexes resulting in an enrichment of C. Other scientists support this finding with data showing that organic C compounds interact more readily with clay than sand or silt particles. A 3D spatial representation of the soil on this landscape was developed. This allowed for calculation of the distribution of C for two horizons and three erosion levels. From the 3D representation and the C content of the top two horizons, it was apparent that there was more C in the Bt1 horizon than in the Ap horizon. This was partially a result of increasing clay content and C associated with the clay as erosion severity increased. However, there was a greater volume of C stored in soil in the slight erosion level than in the moderate or severe erosion level. Data regarding soil C distribution can be very useful for soil management efforts. Additionally, soil C information, such as that presented here, can be valuable in the future for determining possible C storage credits.

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